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The Cold Fusion Phenomenon – What is It?

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Abstract

Present status of the cold fusion (CF) research is reviewed from our point of view to make this field a common heritage of modern science. Various events observed in this field specified by a generic name "cold fusion phenomenon (CFP)" are investigated as a whole from a point of view using a phenomenological model (TNCF model) with a parameter n_n based on the whole experimental facts obtained in materials composed of various host solids and hydrogen isotopes not only deuterium but also protium (cf-materials). The parameter n_n is assumed to be the density of the quasi-stable trapped neutrons (cf-matter) formed in the cf-material. Events used to construct the model include generation of excess energy, emissions of neutrons and charged particles, generation of tritium and helium, and the nuclear transmutation at boundary regions of materials. Numerical relations between numbers of multiple events are explained semi-quantitatively by the model. Empirical laws for observables found in experiments have been used to discuss the cold fusion phenomenon as a complexity thus explaining irreproducibility and sporadicity of events as fundamental natures of the CFP. Bases of the premises assumed in the model, especially the existence of the trapped neutrons, have been investigated quantum mechanically in terms of characteristics of cf-materials. A possible mechanism of an indirect nuclear interaction between lattice nuclei mediated by interstitial hydrogen isotopes (super-nuclear interaction) was proposed. The neutron bands formed by this super-nuclear interaction contribute to formation of the trapped neutrons and even further of the cf-matter. Recent knowledge in nuclear physics and solid state physics is used to give some predictions of possible experiments not known until now. The copper (Cu) is a metal that show high mobility of hydrogen isotopes at higher temperatures than 450 °C and the nucleus has neutron energy levels at around evaporation level (zero level). These characteristics suffice necessary conditions for formation of the neutron bands by the super-nuclear interaction between lattice nuclei in copper hydrides at higher temperatures than 450 °C. So, we may be able to obtain positive data for the CFP in CuH_x and/or CuD_x there. Possible applications of the CFP

are proposed. Though the answer to the question "What is the CFP" is not given at present, we have many materials to solve this riddle in near future. Recent knowledge on atomic nuclei and transition-metal hydrides related to the CFP from our point of view is summarized in Appendix.

1. Introduction

How is it possible to give an evidence of reality for a phenomenon lacking many essential factors common to conventional science developed in the 20th century? This is a question caused by disputes (e.g. [Krivit 2013]) on the article by E. Storms [Storms 2010] published in the *Naturwissenschaften*. In a field where principles governing events are not established such as the cold fusion phenomenon (CFP), the meaning of this term CFP will be explained below, a discussion has to be based on facts with explicit exhibition of a point of view on which the dispute stands. The cold fusion phenomenon (CFP) is the theme at hand originating in the work published almost a quarter of a century ago by Fleischmann et al. [Fleischmann 1989, Kozima 2014]. We will make a trial to open a common field among people with different feelings and opinions to the CFP to discuss this controversial problem positively with each other. Our fundamental point of view is a phenomenological approach based on the experimental data sets as presented by researchers who are reliable to the data. We will not restrain ourselves to such an assumption as *d–d* fusion reactions in solids as the fundamental mechanism for the CFP which restrict our eyes only to the deuterium system neglecting the protium system where are also observed various events supposed to belong to the CFP.

2. Cold fusion phenomenon, cf-materials, and experimental data sets

It is better to define our terminology at first to discuss this complicated and controversial theme, the cold fusion phenomenon (CFP). The "cold fusion phenomenon" is the term we call the events as a whole related to the field originally called "cold fusion" by the pioneering researchers who expected *d–d* fusion reactions in solids composed of host metal (Pd) and deuterium (a kind of hydrogen isotopes). The term "cold fusion phenomena" was first used by Chinese researchers (e.g. [Li 1991]) in the papers presented at ICCF2 in 1991. To clarify the meaning of the term, we redefine it as follows;

The CFP (Cold Fusion Phenomenon) stands for "nuclear reactions and accompanying events occurring in open (with external particle and energy supplies), non-equilibrium system composed of solids with high densities of hydrogen isotopes (H and/or D) in ambient radiation" belonging to Solid-State Nuclear Physics (SSNP) or Condensed

Matter Nuclear Science (CMNS). (CFRL News No.81, http://www.geocities.jp/hjrfq930/).

The cold fusion phenomenon does surely belong to solid-state nuclear physics (SSNP) or condensed matter nuclear science (CMNS) as the superconductivity belongs to conductor physics. However, the SSNP or CMNS is too wide to properly define our meaning included in the CFP that is rather expressed as solid-state nuclear reactions or condensed matter nuclear reactions. We like to clear cut the CFP from such events resulting from the interaction of atomic nuclei with atoms without induced nuclear reactions as Knight shift [Knight 1949], Moessbauer effect [Moessbauer 1958], the change of K-capture probability by environment [Ohtsuki 2004], and neutron guide [Kruegler 1980], neutron trap [Hino 1998, Huffman 2000], etc. belonging also to the SSNP or CMNS. It is necessary to add a comment on the limitation of our research field of the CFP in which there is no artificial acceleration with energies more than 1 keV which adds surplus factors to the events in the CFP.

It is also convenient to define "cf-material" which is the substance where occurs the CFP. The cf-material is composed mainly of a host material (transition metals and alloys) occluding hydrogen isotopes, i.e. protium or/and deuterium, and sometimes of noble and other metals in contact with hydrogen isotopes, and of carbon compounds including hydrogen (e.g. XLPE or cross-linked polyethylene). The composition of the cf-material is various with only a common characteristic of occlusion of hydrogen isotopes with a high density.

We will not describe detailed experimental data sets as far as possible which have been extensively given in books [Kozima 1998, 2006, Storms 2007] and papers cited there*.

Footnote

Papers on the CFP have been published in several journals and also published in Proceedings of Conferences. Many important papers have been cited in the References of the referred books. Papers published in Proceedings of ICCF (International Conference on the Cold Fusion) are printed in the "Contents of Proceedings "posted at CFRL website: http://www.geocities.jp/hjrfq930/Cfcom/Histry/Histry.html.

Papers published in Proceedings of JCF (Japan CF-research Society) are posted at the JCF website: http://jcfrs.org/pubs.html

Some papers published in Conferences are posted at the New Energy Times website: http://newenergytimes.com/v2/conferences/LENRConferenceProceedings.shtml

Many papers published in many places have posted at the following

LENR-CANR.ORG website even if its editorial responsibility is ambiguous: http://lenr-canr.org/

For convenience of readers, we show here tables of experimental data sets given in my book [Kozima 1998 (Tables 11.2 and 11.3)] and cited in the next book [Kozima 2006 (Tables 2.2 and 2.3)] as Tables 2.1 and 2.2. The data obtained by the analyses based on the TNCF model first presented at ICCF4 held in Hawaii, USA in December 1993 [Kozima 1994] are also given in the last two columns of the Tables.

We also will not give evaluation of experimental data sets which is one of targets of the dispute of whether the CFP is real or not. Our point of view about this problem is that we accept data sets as they were presented even if there are some mistakes or misunderstandings in some of many data sets expecting compensation of defects by accumulating a great number of data sets worked out in the period of about a quarter of a century. However, the interpretation of the data given in a paper is a completely different thing from what the data itself tells us. We listen in the experimental data sets themselves even if they show us curious feature but do not necessarily follow the interpretation given there.

Authoritative evaluations of papers of experimental data sets in the CFP have been given in two reports of DOE committees [DOE Report 1989, DOE Report 2004] but with limitations imposed by the requirement to work with the corresponding object papers. The DOE Report 1989 was hasty to deny the occurrence of *d–d* fusion reactions in cf-materials that was the main theme of the CF research at that time. Generation of excess energy by the *d–d* fusion reactions was denied due to the irreproducibility and inconsistency among observed quantities. On the other hand, the DOE Report 2004 was intended to evaluate a paper presented by a group of researchers to show occurrence of a new type of the *d–d* reaction generating excess heat and helium in cf-materials with deuterium. Accordingly, it had a limitation in the scope of its investigation on the CFP. The proposed mechanism of the *d–d* fusion in solids was criticized but the experimental data sets after 1989 were evaluated positively.

The most important fields of the CFP developed after the initial discovery in 1989 are various kinds of events in protium systems and the nuclear transmutations both in deuterium and protium systems which have not been in their targets of the evaluation of the two DOE Reports [DOE Reports 1989, 2004].

Table 2.1 Pd/D(H)/Li System. Neutron density n_n and relations between the numbers N_x of event X obtained by theoretical analysis of experimental data on the TNCF model

($N_Q \equiv Q$ (MeV)/5 (MeV)) [Kozima 2006, Table 2.2]. Typical value of the surface vs. volume ratio S/V (cm^{-1}) of the sample is tabulated, also. As we see here, there are several data sets of the CFP in Pd/H/Li(S) systems even if the combination Pd/D/Li is overwhelmingly preferable for the phenomenon.

Authors	System	S/V cm^{-1}	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
Fleischmann et al.[1)]	Pd/D/Li	6 ~40	Q, t, n $N_t/N_n \sim 4\times10^7$ $N_Q/N_t \sim 0.25$	$\sim 10^9$	(Q=10W/cm^3) $N_t/N_n \sim 10^6$ $N_Q/N_t = 1.0$
Morrey et al.[1−4)]	Pd/D/Li	20	Q, ^{4}He ^{4}He in $\ell \leq 25\mu$m	4.8 $\times10^8$	$N_Q/N_{He} \sim 5.4$ (If 3% ^{4}He in Pd)
Roulette[1''')]	Pd/D/Li	63	Q	$\sim 10^{12}$	
Storms[4)]	Pd/D/Li	9	$t(1.8\times10^2$Bq/mℓ)	2.2×10^7	(τ=250h)
Storms[4')]	Pd/D/Li	22	Q (Q_{max}=7W)	5.5×10^{10}	(τ=120h)
Takahashi et al.[5')]	Pd/D/Li	2.7	t, n $N_t/N_n \sim 6.7\times10^4$	3×10^5	$N_t/N_n \sim$ 5.3×10^5
Miles et al.[18')]	Pd/D/Li	5	Q, ^{4}He ($N_Q/N_{He}=1\sim10$)	$\sim 10^{10}$	$N_Q/N_{He} \sim 5$
Okamoto et al.[12')]	Pd/D/Li	23	Q, NT$_D$ $\ell_0 \sim 1\ \mu$m	$\sim 10^{10}$	$N_Q/N_{NT} \sim 1.4$ (^{27}Al$\rightarrow$^{28}Si)
Oya[12−5)]	Pd/D/Li	41	Q, γ spectrum	3.0×10^9	(with^{252}Cf)
Arata. et al.[14)]	Pd/D/Li	7.5 $\times10^4$	Q, ^{4}He ($10^{20}\sim10^{21}$ cm^{-3}) $N_Q/N_{He} \sim 6$	$\sim 10^{12}$	(Assume t channeling in Pd wall)
McKubre[3)]	Pd/D/Li	125	Q (& Formula)	$\sim 10^{10}$	Qualit.explan.
Passell[3''')]	Pd/D/Li	400	NT$_D$	1.1×10^9	$N_{NT}/N_Q=2$
Cravens[24'')]	Pd/H/Li	4000	Q (Q_{out}/Q_{in}=3.8)	8.5×10^9	(If PdD exists)
Bockris[43)]	Pd/D/Li	5.3	t, ^{4}He; $N_t/N_{He} \sim 240$	3.2×10^6	$N_t/N_{He} \sim 8$
Lipson[15−4)]	Pd/D/Na	200	γ (E_γ=6.25MeV)	4×10^5	If effic. =1%
Will[45)]	Pd/D_2SO_4	21	$t(1.8\times10^5$/cm^{2}s)	3.5×10^7	(If $\ell_0 \sim 10\mu$m)
Cellucci et al.[51''')]	Pd/D/Li	40	Q, ^{4}He $N_Q/N_{He}=1\sim5$	2.2×10^9	(IfQ=5W) $N_Q/N_{He}=1$
Celani[32''')]	Pd/D/Li	400	Q (Q_{max}=7 W)	1.0×10^{12}	(If200%output)
Ota[53)]	Pd/D/Li	10	Q (113%)	3.5×10^{10}	(τ=220 h)
Gozzi[51'')]	Pd/D/Li	14	Q, t, ^{4}He	$\sim 10^{11}$	($\tau \sim 10^3$h)
Bush[27')]	Ag/PdD/Li	2000	Q (Q_{max}=6W)	1.1×10^9	(τ=54d,Film)
Mizuno [26−4)]	Pd/D/Li (If Cr in Pd)	3.4	Q, NT$_D$ $\ell \leq 2\ \mu$m)	2.6×10^8	τ=30d,Pd 1cm$\phi\times$10cm
Iwamura[17)]	PdD$_x$	20	n (400/s),t	3.9 $\times10^8$	4.4 $\times10^6 t$/s
Itoh[17')]	PdD$_x$	13.3	n (22/m),t	8.7 $\times10^7$	7.3 $\times10^{10} t$/s
Itoh[17'')]	PdD$_x$	13.3	n (2.1 $\times10^3$/s)	3.9 $\times10^8$	
Iwamura [17''')]	PdD$_x$	20	Q (4 W) NT$_F$(Ti, Cr etc.)	3.3 $\times10^{10}$	(NT$_F$? unexplained)
Miley[65)]	Pd/H/Li	150	NT$_F$(Ni,Zn,$\cdots\cdots$)	4.5 $\times10^{12}$	
Dash[59)]	Pd/D,H_2SO_4	57	Q, NT$_D$	$\sim 10^{12}$	Pt$\rightarrow$Au
Kozima[203)]	Pd/D,H/Li	200	n (2.5×10^{-4}/s)	2.5 $\times10^2$	Effic. =0.44%

Table 2.2. Ni/H/K System and others. Neutron density n_n and relations between the numbers N_X of event X obtained theoretical analysis of experimental data on TNCF model ($N_Q \equiv Q$ (MeV)/5 (MeV)) [Kozima 2006, Table 2.3]. Typical value of the surface vs. volume ratio S/V (cm^{-1}) of the sample is tabulated, also. As we see here, there are several data sets of the CFP in Ni/D/K systems even if the combination Ni/H/K is overwhelmingly preferable for the phenomenon.

Authors	System	S/V cm^{-1}	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
Jones[2)]	Ti/D/Li	8.1	n (2.45 MeV)	3.1×10^{11}	
Mills[25)]	Ni/H/K	160	Q (0.13 W)	3.4×10^{10}	
Bush[27')]	Ni/H/K Ni/H/Na	~160 ~160	NT_D(Ca) NT_D(Mg)	5.3×10^{10} 5.3×10^{11}	$N_Q/N_{NT}\sim3.5$ ($^{40}K_T=0$)
Bush[27'')]	Ni/H/Rb	$\sim10^4$	NT_D(Sr)	1.6×10^7	$N_Q/N_{NT}\sim3$
Savva-timova[34'')]	Pd/D_2	100	NT_D(Ag)	9×10^{10}	
Alekseev[44')]	Mo/D_2	4.1	t ($\sim10^7$/s)	1.8×10^7	(If MoD)
Romoda-nov[44''')]	TiC/D	4.1	t ($\sim10^6$/s)	$\sim10^6$	(D/Ti~ 0.5assumed)
Reifensch-weiler[38')]	$TiT_{0.0035}$	7×10^5	β decay reduction	1.1×10^9	(T=0~450°C)
Dufour[7)]	$Pd,SS/D_2$ $Pd,SS/H_2$	48	Q, t, n	9.2×10^{11} 4.0×10^9	(D(H)/Pd~1 is assumed)
Claytor[9)]	Pd/D_2	400	t (12.5 nCi/h)	1.6×10^{13}	(If D/Pd~0.5)
Srinivasan[16)]	Ti/D_2	1500	t ($t/d\sim10^{-5}$)	1.9×10^8	(Aged plate)
De Ninno[6')]	Ti/D_2	440	n , t	1.2×10^6	(D/Ti=1,1w)
Focardi[23)]	Ni/H_2	8.2	Q	3.0×10^{12}	(If$N_p=10^{21}$)
Oriani[52)]	$SrCeO_3/D_2$	22	$Q\sim0.7$W	4.0×10^{10}	V=0.31cm^3
Notoya[35'')]	Ni/D,H/K	3.4 $\times10^4$	Q (0.9 W), t	2.4×10^{13}	(If 1/2 t is in liquid)
Notoya[35−4)]	Ni/D,H/K	same	NT_D(Ca)	1.4×10^9	(Sintered Ni)
Yamada[54)]	Pd/D_2	185	n , NT_D(C)	2.0×10^{12}	
Cuevas[55)]	$TiD_{1.5}$	134	n (102 n /s)	5.4×10^{11}	
Niedra[56)]	Ni/H/K	80	Q (11.4 W)	1.4×10^9	5km×0.5mmϕ
Ohmori[22'')]	Au/H/K	200	Q, NT_F(Fe)	$\sim10^{11}$	(Au plate)
Li[57)]	Pd/D_2	185	Q	1.6×10^{12}	(Pd wire)
Qiao[57')]	Pd/H_2	185	NT_F(Zn)	3.8×10^{10}	(40%NTin 1y)
Bressani[58')]	Ti/D_2	$\le10^3$?	n (ε)	10^5-10^6	(Ti shaving)
Miley[65')]	Ni/H/Li	50	NT_D(Fe,Cr,···)	1.7×10^{12}	

It should be emphasized first that the CFP occurs not only in deuterium but also in protium systems. For a long period after 1989, there remained people even in the CF researchers who are reluctant to recognize the occurrence of the CFP in protium systems persisting in the reactions (2.1) – (2.3) below (in the free space) generating excess energy Q (in MeV);

$$d+d\to {}^4_2He^* \to t\,(1.01)+p\,(3.02),\qquad Q=4.03 \tag{2.1}$$
$$\to {}^3_2He\,(0.82)+n\,(2.45),\qquad Q=3.27 \tag{2.2}$$
$$\to {}^4_2He\,(0.07)+\gamma\,(23.66).\qquad Q=23.73 \tag{2.3}$$

It is regrettable to know that there are scientists who are restricting their sight themselves by the negligence of the unexpected facts betraying their expectation. If we want to find a common cause of peculiar events in both deuterium and protium systems, we have to open our eyes to experimental facts themselves obtained in both systems.

3. Irreproducibility, sporadicity, and conceptual incoherence

Now, we would like to discuss several causes of discrepancy between pros and cons in evaluation of works in the CFP; irreproducibility, sporadicalness (sporadicity), and conceptual incoherence.

3.1 Irreproducibility

In general, reproducibility of an event is a characteristic in simple systems governed by differential equations while it is not in complex systems where events are described by nonlinear dynamics.

The phase transition of transition-metal hydrides and deuterides, e.g. PdH_x, is the manifestation of nonlinear interaction of hydrogen atoms and host metals. The palladium hydride PdH_x makes transition from the *fcc* ($\alpha + \beta$) phase solution to the *fcc* β phase hydride at $x = 0.63$. (The α phase is a solution made of H in an octahedral site of *fcc* Pd lattice and the β phase is a hydride where H^+ occupies at an octahedral site) [Flanagan 1978].

The super-lattice composed of the host lattice and the interstitial lattice of hydrogen (or deuterium) is governed by the atomic process of the hydrogen migration through the host lattice which is influenced by the occupation rate of interstitial sites. Furthermore, if our speculation is correct, the formation of the super-lattice PdH is influenced by the super-nuclear interaction of lattice nuclei mediated by interstitial protons. This interaction has nonlinear character due to its origin depending on the geometric arrangement of protons in the interstices. The formation of the cf-matter in surface regions of a cf-material where the superlattice is realized is determined by nonlinear processes as discussed in our papers [Kozima 2012, 2013].

In addition to this atomic characteristic of transition-metal hydrides deuterides, it is our common sense that events in nuclear physics are statistical and not deterministic as the simple example of the alpha-decay shows. If an event is caused by an uncontrollable microscopic change in a nuclear system and is directly combined to the cause, then the effect observed macroscopically is governed by the microscopic process and is therefore statistical. The detection of the effect is inevitably stochastic and not reproducible individually. Simple example is useful to elucidate the situation; if the effect is observed separately for an individual event but not as an averaged quantity over many events (as many nuclear processes are the cases); the stochastic nature of the event should be emphasized. Sudden bursts of excess heat and neutron emission observed in several

experiments have showed such stochastic and sporadic nature in the CFP.
These two phases of the CFP, one the nonlinear nature of cf-matter formation and another statistical nature of the nuclear reactions, result in irreproducibility of the events in the CFP.

3.2 Sporadicalness (Sporadicity)

Sporadic occurrence of events in the CFP is another characteristic of this field. To express sporadic character of events, we would like to propose to use new word "sporadicity" while there is lengthy word "sporadicalness" in a dictionary. Then, sporadicity of the events in the CFP is explained by statistical formation of optimum conditions for the occurrence of a microscopic situation where caused events observed as a macroscopic observable such as excess energy and neutron emission explained above in relation to the irreproducibility.

3.3 Conceptual incoherence

The most subtle and difficult problem to explain is consistency of experimental facts as a whole with the framework of the modern science developed in 20th century. A point of view to investigate experimental data sets of observables in the CFP is decisively important in relation to this problem. It is necessary to take whole experimental facts into consideration not discarding data sets unfavorable for a point of view to construct a science based on the facts. It is difficult to distinguish the simple system described by differential equations that is we have used to study in nuclear physics from the complex system described by nonlinear dynamics in which the CFP belongs to. As we have suggested in our papers [Kozima 2012, 2013] and will show below, events in the CFP seem to be characterized by complexity. The irreproducibility and the sporadicity explained above is a natural conclusion of the complexity if cf-materials are essentially the proper object which should be treated by the nonlinear dynamics.

4. Experimental facts and cf-materials in general

We summarize experimental systems and observed facts in Table 4.1 to show vast amount of information obtained in the CFP in these about 25 years.
This table shows that the cold fusion phenomenon (CFP) occurs in various solids with various agents and its contents are very complex.
Agents necessary for CFP known by now are hydrogen isotopes, i.e. hydrogen H (proton *p*) and deuterium D (deuteron *d*), neutron *n*, lithium-6 (^{6}Li), boron-10 (^{10}B), potassium-39 (^{39}K), rubidium-85 and -87 (^{85}Rb and ^{87}Rb). It is, however, not well known

what is actually necessary for the host solids and the agents to induce the CFP, i.e. the necessary conditions of the CFP are not quantitatively determined at all.

Tending to be overlooked is the existence of background neutrons which is one of the necessary conditions to induce the CFP as several experimental data sets had clearly shown; when there are no background neutrons, no CFP is observed and when artificial thermal neutrons are irradiated, the CFP is intensified as explained in Section 2.2 (d) of the book [Kozima 2006].

Table 4.1. System and Obtained Evidence of the CFP: Host solids, agents, experimental methods, direct and indirect evidence, cumulative and dissipative observables are tabulated. Q and NT express excess energy and the nuclear transmutation, respectively. Direct evidence of nuclear reactions in the CFP are dependences of reaction products on their energy (ε) and position ($\boldsymbol{r}$), decrease of decay constants of radioactive nuclides, decrease of fission threshold energy of compound nuclei.

Host solids	Pd, Ti, Ni, KCl + LiCl, $ReBa_2Cu_3O_7$, Na_xWO_3, KD_2PO_4, TGS (triglycinesulfate), $SrCe_aY_bNB_cO_d$, XLPE (cross linked polyethylene)
Agents	*n, d, p*, $^{6}{}_{3}Li$, $^{10}{}_{3}B$, $^{39}{}_{19}K$, $^{85}{}_{37}Rb$, $^{87}{}_{37}Rb$
Experiments	Electrolysis, Gas discharge, gas contact
Direct evidences of nuclear reaction	Gamma ray spectrum γ(ε), Neutron energy spectrum n(ε), Space distribution of NT products NT($\boldsymbol{r}$), Decrease of decay constants, lowering of fission threshold energy
Indirect evidences of nuclear reaction	Excess energy Q, Number of neutrons N_n, Amounts of tritium atom N_t, helium-4 atom* N_{He4}, NT products (NT_D, NT_F, NT_A), X-ray spectrum X(ε)
Cumulative observables	NT($\boldsymbol{r}$), amount of tritium atom N_t, helium-4* N_{He4},
Dissipative observables	Excess energy Q, neutron energy spectrum n(ε), number of neutrons N_n, Gamma ray spectrum γ(ε), X-ray spectrum X(ε),

*It should be given a comment on the observation of helium-4. The quantitative observation of helium-4 is extremely difficult as an expert of helium measurement once pointed out [Kozima 2002]. So, we have to be careful to interpret an experimental data set when they include a quantitative detection of helium.

Direct evidence of nuclear reactions is events clearly resulting from nuclear reactions from common sense of present physics. The following events belong in this category; emission of gamma ray, neutrons with definite energy, generation of new nuclides (including possible occurrence of nuclear fission), changes of decay constants of radiative nuclides.

Indirect evidence of nuclear reactions are events most appropriately explained by nuclear reactions; excess energy of huge amount inexplicable by chemical reactions or physical processes, extraordinary increase of number of neutrons, increase of tritium amount, increase of helium-4, appearance of X-ray radiation, and so on.

The cumulative and dissipative observables give a measure of reliability of experimental data on them. Generally speaking, cumulative observables have higher reliability on the measured values than the dissipative ones have.

It should be noticed that events classified in direct and indirect evidences in Table 4.1 are not necessarily observed at the same time. Rather, it is rarely the case that two or more events are observed simultaneously. Some examples of these rare cases are tabulated in the book [Kozima 1998, 2006]. Usually, excess heat is observed along with some other events, e.g. tritium and neutron, or nuclear transmutation (NT). In such lucky cases where measured several observables simultaneously, we can have an important clue to determine the mechanism for reactions resulting in these observables.

As explained in the next section, we have determined the numbers of reactions giving two or three observables using an adjustable parameter to give satisfactory coincidence with corresponding numbers obtained by experiments [Kozima 1998 (Section 11.1b), 2006 (Section 3.3.1)].

5. A phenomenological model (TNCF model)

The TNCF model [Kozima 1998, 2006] with a single adjustable parameter n_n is based on the whole experimental facts obtained in materials composed of various host solids and hydrogen isotopes not only deuterium but also protium. Events used to construct the model include generation of excess energy, emission of neutrons, emission of charged particles, generation of tritium and helium, and nuclear transmutation at boundary regions of materials. When we analyze experimental data sets of several observables determined simultaneously, we could determine the parameter n_n by an observable and then calculates another observable by the recipe of the model using the determined parameter to compare with its experimental data. The comparisons have been successful semi-quantitatively.

One of the most interesting results explained by the TNCF model is the ratios of numbers N_x's of plural events X's observed simultaneously. Determining the parameter n_n by the data of the number N_x of an event X, we can calculate the number N_y of another event Y using the model and compare the theoretical ratio $(N_x/N_y)_{th}$ thus calculated with the experimental value $(N_x/N_y)_{ex}$. We have obtained fairly good coincidence of these values in a factor about 3 as expressed by the following relation [Kozima 2006, Sec. 3.3.1]:

$$(N_x/N_y)_{th} = \alpha(N_x/N_y)_{ex} \qquad (5.1)$$

with $\alpha \sim 3$. The events X's used are excess energy Q (N_Q), amounts of generated tritium (N_t) and helium-4 (N_{He4}) and product nucleus of nuclear transmutation (N_{NT}).

Details of the model are explained in the books [Kozima 1998, 2006] and papers (for example [Kozima 2008a]). The success of this approach substantiated the assumption of the trapped neutrons in cf-materials and the basis of the assumption has been investigated quantum mechanically which is left for the references (e.g. [Kozima 2008c]). The cf-matter is the concept worked out in relation to the neutron bands formed by the super-nuclear interaction between lattice nuclei mediated by interstitial hydrogen isotopes corresponding to the assumed trapped neutrons in the TNCF model [Kozima 2006, Sec. 3.7.5]. Necessary conditions for realization of the cf-matter are given in Appendix to this paper.

6. Three empirical laws in the CFP

The three empirical laws (or regularities) [Kozima 2012] found in our course of research show that the CFP is a phenomenon belonging to complexity. The irreproducibility of events in the CFP discussed in Sec. 3 is closely related to the complexity in this phenomenon. We explain them below as a material for discussion.

6.1 1/*f* dependence of excess energy production ("inverse-power law")

In several experimental data sets, we are able to count numbers (frequency) N_Q of an event with a specific amount of excess energy Q (or an excess power P) and plot them as a function of Q (or P) obtaining N_Q vs. Q (or P) plot [Kozima 2006, Sec. 2.12]. The first plot was obtained for the data by McKubre et al. [McKubre 1993]. This plot clearly shows that there is an inverse-power relation of frequency vs. intensity with an exponent p of 1, famous in complexity. This regularity may be called the inverse-power dependence of frequency on intensity of the excess energy production ("inverse-power law"). The inverse-power law has been shown also for a data set obtained by Kozima et al. (with $p = 2$) [Kozima 2008b] and those compiled by Storms [8] (with $p = 1.0$) [Lietz 2008] as shown in Fig. 6.1.

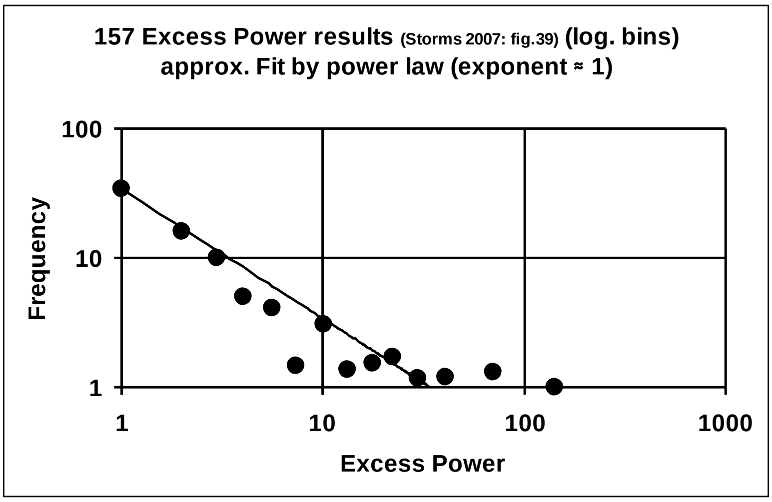
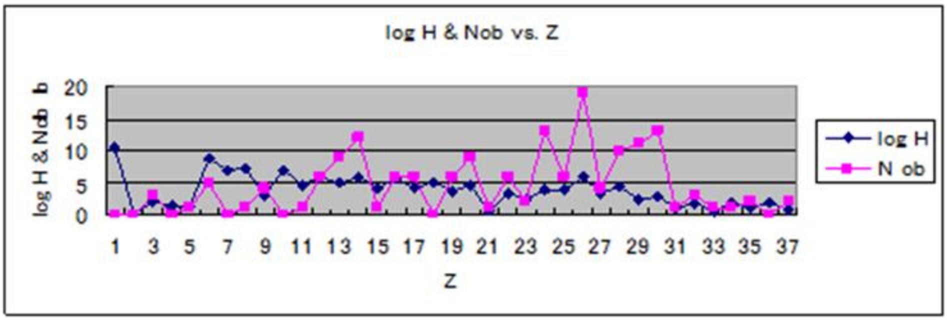


Fig. 6.1. Distribution of 157 excess energy results by Lietz [Lietz 2008] using the data collected by Storms [Storms 2007]. Values have been stored in bins of size 10. The line shows a power-law fit to the binned data with an exponent of 1.0 (r^2 = 90%) (Fig. 3 of [Lietz 2008])

6.2 Stability effect on the nuclear transmutation products ("stability law")

If we survey numbers of elements produced by the nuclear transmutation in the CFP, we notice the frequency obtaining an element has a positive correlation with the amount of the element in the universe [Kozima 2006, Sec. 2.11]. Plotting out (i) the number of experiments where observed an elements ${}_Z X$ together with (ii) the amount in the universe compiled by Suess and Urey [Suess 1956] against its proton number Z, we obtain a diagram showing the coincidence of the peaks of (i) and (ii), which gives the stability effect for nuclear transmutation products [Kozima 2010a] as shown in Fig. 6.2. We may call this regularity the "stability law" for nuclear transmutation in the CFP.

(a)



(b)

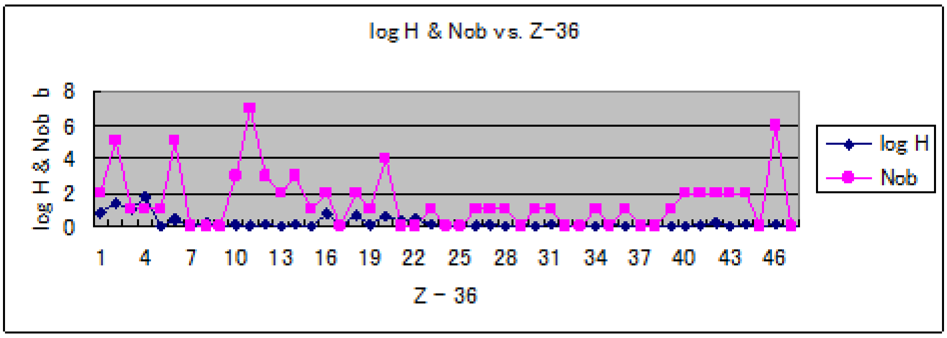


Fig. 6.2. Correspondence between the frequency $N_{ob}(Z)$ observing elements in the CFP and the relative abundances $\log_{10}H(Z)$ of elements in the universe [Suess 1956]: (a) $Z = 3 - 38$ and (b) $Z = 39 - 83$ [Kozima 2006]

6.3 Complexity of events ("bifurcation law")

The third law in the CFP is a little subtle to show it compared with the former two. Even if the number of examples is scarce, we have several fortunate data sets of temporal evolution of effects in the CFP. The first one is that of neutron emission from TiD_x by De Ninno et al. published in 1989 [De Ninno 1989]. Another data set is the excess heat generation observed by McKubre et al. in 1993 [McKubre 1993]. Furthermore, we can cite another example of the temporal evolution of excess energy generation measured by Kozima et al. in 2008 [Kozima 2008b]. The data by McKubre et al. is shown in Fig. 6.3. The empirical feature of these temporal evolutions of observables is similar to the bifurcation of the solutions of an equation in nonlinear dynamics shown in Fig. 6.4 [Kozima 2012]. This is what we call the "bifurcation law".

By the nature of events in complexity, we can give only qualitative explanation of an experimental result in analogy to the mathematical results of numerical simulations for the logistic difference equation. The analogical explanations of the laws observed in the CFP have been given using the Feigenbaum's theorem describing a nature of an equation of nonlinear dynamics [Kozima 2012, 2013].

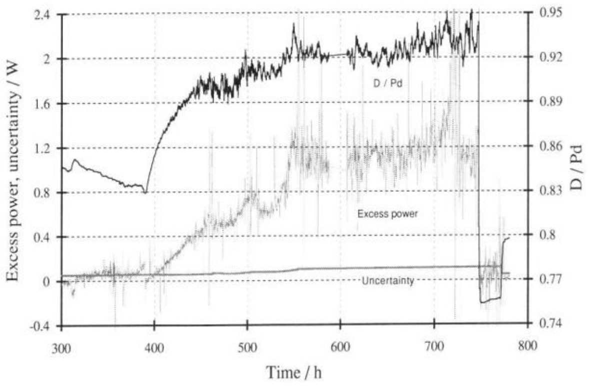


Fig. 6.3. Variation of Excess Power, Uncertainty and Loading ratio [McKubre 1993].

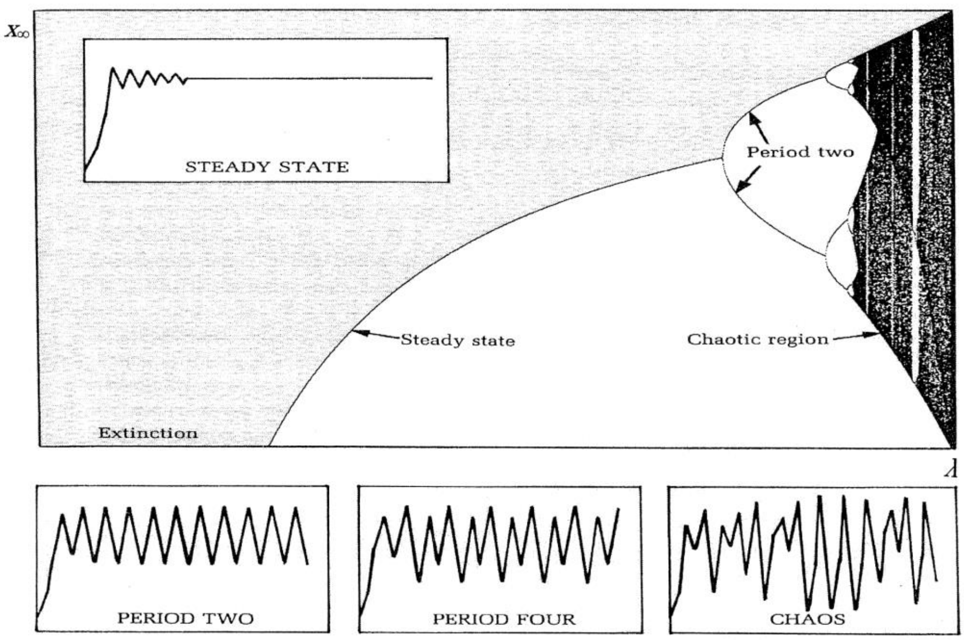


Fig. 6.4 Bifurcation diagrams ([Gleick 1987], page 71).

7. Conclusions

The cold fusion phenomenon (CFP) has been a controversial theme in the interdisciplinary region between solid state physics and nuclear physics. As has been shown above, the CFP observed in cf-materials containing hydrogen isotopes (deuterium or/and protium) is too complicated to be explained only by some simple extrapolations of knowledge established in solid-state nuclear physics (or condensed matter nuclear science) developed in 20th century. If it is reflecting something real in entity not noticed before 1989, there should be a fundamentally new physics hidden under the cloud of various events observed in the CFP and in turn the physics should reveal the existence of new events in solid state physics and nuclear physics. Our effort in this field should also be in the direction to find out what we can say about these new phenomena reflected from the CFP in the traditional research fields of physics.

On the other hand, the TNCF model fairly successful to explain the CFP as a whole at present will serve as a first step in the right direction to the science of this new field. The model shows that the new physics should be a science including a new state of neutrons in cf-materials. Furthermore, if we notice that the CFP is characterized by complexity, we have to treat the cf-material, the superlattice composed of a host sublattice (host nuclei at the lattice points) and a proton (deuteron) sublattice (protons (deuterons) at the interstitials) as a whole taking into nuclear reactions among host nuclei and interstitial protons (deuterons).

From our point of view using a phenomenological approach [Kozima 1994, 1998, 2004, 2006], the idea of the cf-matter resembling to the neutron sea appeared in the investigation of the neutron star matter is the most hopeful entity having close connection with neutron physics developing in nuclear physics. We have a lot novel knowledge of neutron interaction in isolated exotic nuclei behaving differently from the traditional concept of nuclear force in the nucleus [Kozima 2014a]. Furthermore, when a nucleus is not isolated and connected with other nuclei through the super-nuclear interaction, nuclear force between lattice nuclei mediated by protons or deuterons at interstitials with wavefunctions extended over lattice points as figured out in our model, we may have a new perspective of neutron physics in hydrogenated solids resulting in new features of nuclear physics not found in isolated particles considered by now.

Some new materials supporting our model are presented in Appendix to supplement our explanation given in papers and books published before [Kozima 2006, 2008c] and briefly discussed their relation to the TNCF model.

In conclusion, the answer we can give to the question "What is the cold fusion phenomenon (CFP)?" is "It is a riddle" at present when we do not know the complete necessary and sufficient conditions for the CFP. If the science of the CFP is established on the line suggested by our phenomenological approach, the vista of future science as the physics of neutrons in hydrogenated solids is wide and endless. We can not overview its development in future correctly at present.

It should be discussed briefly possible applications of the CFP. The events observed in the CFP, e.g. excess energy production and nuclear transmutation, are naturally considered to be used in commercial devices. There, however, remain several limitations for their effective application due to the essential characteristics of this phenomenon.

One is the sporadicity of the events and another is the short durability of working cf-materials which has been shown as defects generated at the surface of cf-materials where have occurred events of the CFP. Furthermore, we have to care emergence of radioactive emissions of neutrons and charged particles in the cf-materials. The sporadicity of the events will be overcome if we know the necessary and sufficient conditions for the events by development of science of the CFP. The durability of the working materials will be improved by the science of the CFP or remedied by such a technical invention to replace new working elements regularly. The hazardous radioactivity could be prevented by appropriate protection facilities.

Appendix

Some Characteristics of Lattice Nuclei and Interstitial Hydrogen Isotopes in CF-Materials related to the Formation of the CF-Matter for the Cold Fusion Phenomenon

As we have investigated hitherto, the cold fusion phenomenon (CFP) has close relation with the property of lattice nuclei on one hand and with the property of interstitial hydrogen isotopes on the other.

First of all, it is necessary to have a cf-material where is a superlattice composed of a sublattice of a host element and another of a hydrogen isotope. In addition to this condition, there are some necessary conditions on the lattice nucleus and the interstitial hydrogen isotope to realize the super-nuclear interaction between lattice nuclei for formation of the neutron bands and accordingly of the cf-matter in a cf-material. The nucleus of a host element on the lattice points of a cf-material (lattice nucleus) should have a neutron wavefunction with large extension. The interstitial hydrogen isotope (proton or deuteron on interstitial sites), on the other hand, should have a wavefunction extending over nearest neighbor lattice points. Then, we can expect the super-nuclear interaction between neutrons in lattice nuclei mediated by interstitial hydrogen isotopes. This scenario for the CFP has supports from recent knowledge of nuclear physics and solid state physics as briefly explained below in addition to the data we have used in our former books and papers [Kozima 2006, 2008c, 2013].

In this appendix, we give this recent knowledge as follows:

A1. Neutron levels at around evaporation level (zero level)

A1-1 Cross-linked Polyethylene (XLPE) $[CH_2]_n$

A1-2 ${}^{A}_{24}Cr$ (A = 50 -54)

A1-3 ${}^{63}_{29}Cu$ and ${}^{65}_{29}Cu$

A1-4 $^{A}_{30}Zn$ (A = 64 – 70)

A1-5 Al_2CuH_x

A2. Exotic nucleus with a large excess number of the neutron

A3. Diffusion coefficient of isotopes of hydrogen in Pd, Ni, and Cu

A4. Mean-square displacements of hydrogen atoms in V, Nb, Ta and Pd

A1. Neutron levels at around evaporation level (zero level)

The super-nuclear interaction between lattice nuclei mediated by interstitial protons or deuterons may have a close relation to the neutron energy levels at around the evaporation levels (levels at around zero) which have wide-spread wavefunctions. Energies of neutron orbits in a nucleus with a nucleon number A calculated by C.J. Veje [Bohr 1969] are shown in Fig. A1 (for A = 18 – 210). Many examples for modification of shell structure in neutron-rich nuclei have been known recently [Wiedenhover 2007]. Therefore, the energies of neutron orbits at around zero energy shown in Fig. A1 may be altered by formation of neutron-rich exotic states of relevant nuclei. We use this figure, however, for our investigation of the CFP because we have no data of recent information about them at present.

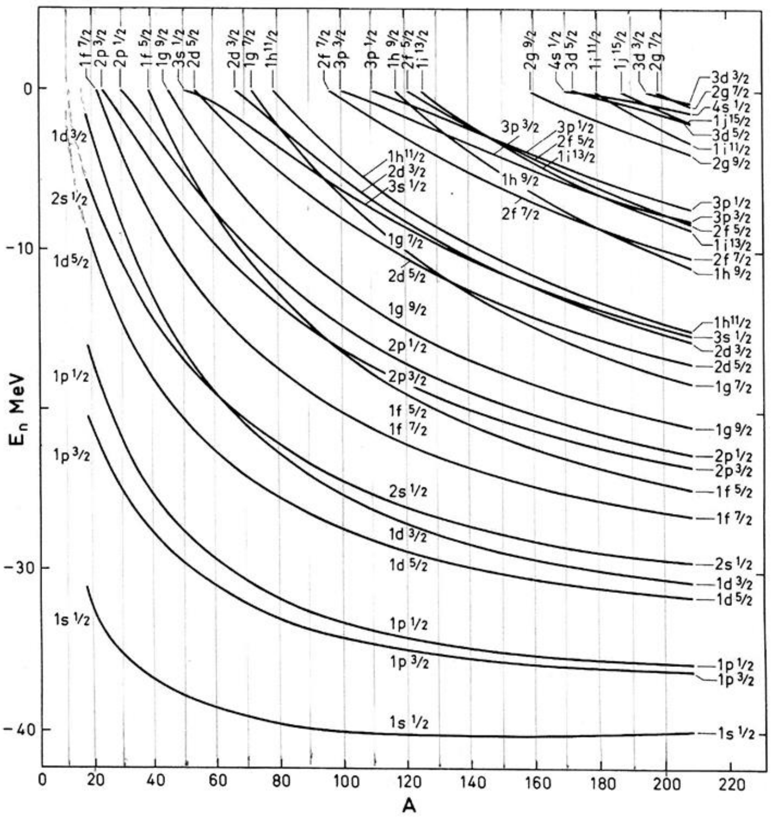


Fig. A1. Energies of neutron orbits in nuclei calculated by C.J. Veje [Bohr 1969]

The CFP is most frequently observed in transition-metal deuterides and hydrides, especially in TiD (H), NiH (D), and PdD (H). Furthermore, these transition-metal nuclei have a common characteristic; existence of excited neutron levels near zero in an isolated nucleus, $3s_{1/2}$ in ${}^{A}_{22}Ti$ (A = 46 ~ 50), $3s_{1/2}$ in ${}^{A}_{28}Ni$ (A = 58 ~ 64), and $3p_{3/2}$ and $3p_{1/2}$ in ${}^{A}_{46}Pd$ (A = 102 ~ 110) as shown in Fig. A1 [Bohr 1969]. As discussed in books and papers [Kozima 2006 (Sec. 3.6), 2012] and in Secs. A3 and A4 in this Appendix, the wavefunctions of protons and deuterons in these compounds show extended nature asked for the super-nuclear interaction.

Therefore, the CFP observed in PdH (D), TiD (H) and NiH (D) is a typical illustration of the mechanism proposed by our model.

Interesting cases of XLPE ($[CH_2]_n$), CrH_x, CuH_x, ZnH_x and Al_2CuH_x are discussed successively in this Section.

A1-1 Cross-linked Polyethylene (XLPE) $[CH_2]_n$

A wonderful experimental data of water-tree formation had been obtained in XLPE used for shielding of wires to transmit the electric power and explained by the TNCF model as a phenomenon showing nuclear transmutations at boundary regions of spherulite and amorphous phase [Kozima 2010b]. This data has shown that carbon is responsible to the CFP if regular arrays of carbon and hydrogen isotopes are formed. From our point of view that the CFP is realized when there is the super-nuclear interaction between lattice nuclei (in this case C) mediated by interstitial protons or deuterons. Looking into Fig. A1, we see there may be a neutron level $1d_{3/2}$ and possibly another one $2s_{1/2}$ for a ${}^{12}_{6}C$ nucleus extrapolating the curve at A = 20 to left. If this extrapolation is permissible, the explanation of the data obtained in XLPE by the CFP will have another support from knowledge of nuclear physics.

A1-2 ${}^{A}_{24}Cr$ (A = 50 -54)

In this case, we see there is a level 3s1/2 at around A = 50 – 53. Chromium (Cr) crystalizes in a *bcc* lattice and becomes *hcp* and *fcc* lattices as a high-temperature phase at high pressures by absorption of hydrogen isotopes [Fukai 2005, Tables 2.4 and 2.5]. Therefore, CrH_x or CrD_x will be a cf-material at high temperatures where these hydrides are realized by the mechanism (the super-nuclear interaction) explained in A1-1.

A1-3 ${}^{63}_{29}Cu$ and ${}^{65}_{29}Cu$

As we see in Fig. A8, copper (Cu) has similar characteristic of hydrogen diffusion to Pd at a high temperature region above 450 °C. From only this property of a large diffusion constant for hydrogen diffusion (suggesting extended proton wavefunctions), we can expect that the CFP will occur in Cu in this temperature region inconsistent with the experimental facts. This contradiction will be understood by the absence of neutron levels at zero energy for copper nuclei with A = 63 and 65 as we see in Fig. A1.

A1-4 $^{A}_{30}$Zn (A = 64 – 70)

In this case, we see there is a level $2d_{3/2}$ at around A = 66 – 70 for zinc (Zn). This state is responsible to the super-nuclear interaction if there are occluded hydrogen isotopes at interstitial sites. However, we do not know if Zn is responsible for hydrides formation. This fact excludes Zn from a host element for a cf-material.

A1-5 Al_2CuH_x

It is reported in a recent paper by Saitoh et al. [Saitoh 2013] that an interstitial alloy Al_2CuH_x is a good material for storage of hydrogen isotopes. The structure is shown in Fig. A2. As explained above, Cu is not possible to give a neutron state at zero energy. On the other hand, $^{27}_{13}$Al has no zero energy states as we see in Fig. A1. So, this material will not show the CFP and stable against nuclear reactions. This property will be preferable for a material to store hydrogen in it.

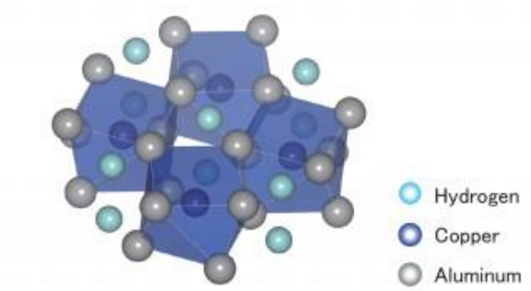


Fig. A2. Structure of the interstitial alloy Al_2CuH_x [Saitoh 2013].

A2. Exotic nucleus with a large excess number of the neutron

It is well known that exotic nuclei with large excess numbers of the neutron over that of the proton have neutron halos around the nuclear core. One example of these halo structure of $^{11}_{4}$Be is shown in Fig. A3.

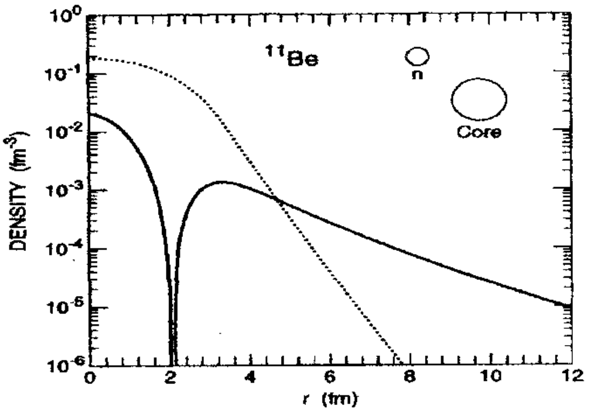


Fig. A3. Plot of the $^{11}{}_{4}Be$ density [Riisager 1994]. The upper right cornet shows the simplified picture of a halo nucleus as a two-body system with an inert core and a halo neutron. Dotted line, core density as a function of radius; solid line, the density obtained in a Hartree –Fock calculation with the neutron in a $2s_{1/2}$ orbital and a single-neutron separation energy adjusted (to agree better with experiment) to 0.51 MeV. Note the very far-extended, dilute tail that is the characterizing feature of a halo [Riisager 1994].

Recent investigations of the exotic nucleus have shown characteristic interactions between neutrons different from that between neutron and proton [Kanungo 2011, Lu 2013]. These features of exotic nuclei about neutron behavior at a relatively thin density may have some relation with peculiar properties of the cf-matter worked out by the investigation of the CFP using the TNCF model

It is not known the relation between these excited neutron levels at around the zero energy level (cf. Fig. A1) and the neutron halo in exotic nuclei at present even if we know that "Neutron-rich nuclei have shell structure different from their "stable" siblings and their proton-rich mirrors!" [Wiedenhover 2007]. From the viewpoint of the CFP, the relation of the excited neutron levels and the neutron halo should be very close and these neutron levels are contributing to the stabilization of the exotic nuclei of the corresponding nuclides in cf-materials. Therefore, the investigations on the CFP in PdH(D), TiD(H) and NiH(D) systems will give information about neutron halo in exotic nuclei at lattice points, the wavefunction of protons or deuterons at interstices, and their interaction if our expectation is true.

Another example of neutron halos of $^{6}{}_{2}He$ and $^{8}{}_{2}He$ is given in Fig. A4. In this figure, we can see a fairly good coincidence between theory and experiment showing advance in theoretical understanding of nuclear structure.

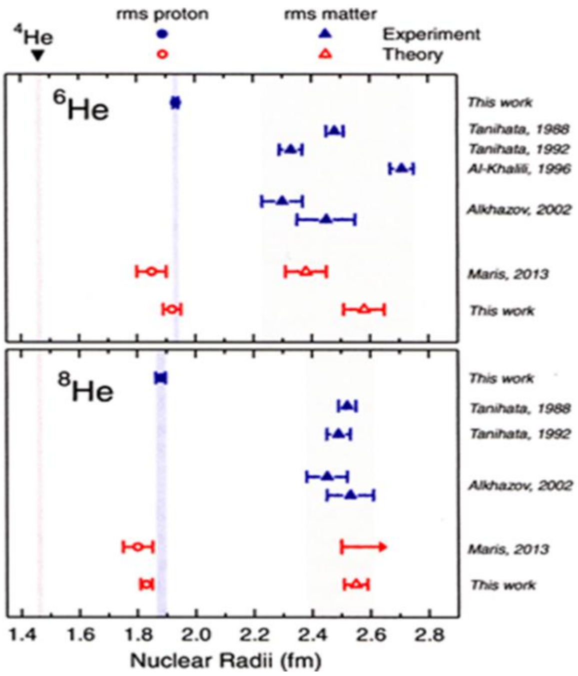


Fig. A4. Comparison between experimental and theoretical values of point-proton and matter radii for ^{6}He (top panel) and ^{8}He (bottom panel) [Lu 2013, Fig. 8]

The investigation of exotic nuclei is not limited to the structure of neutron halo but gives us much information about the nucleus. The data shown in Fig. A5 is the two-neutron separation energy S_{2n} as a function of the neutron number N of exotic nuclei.

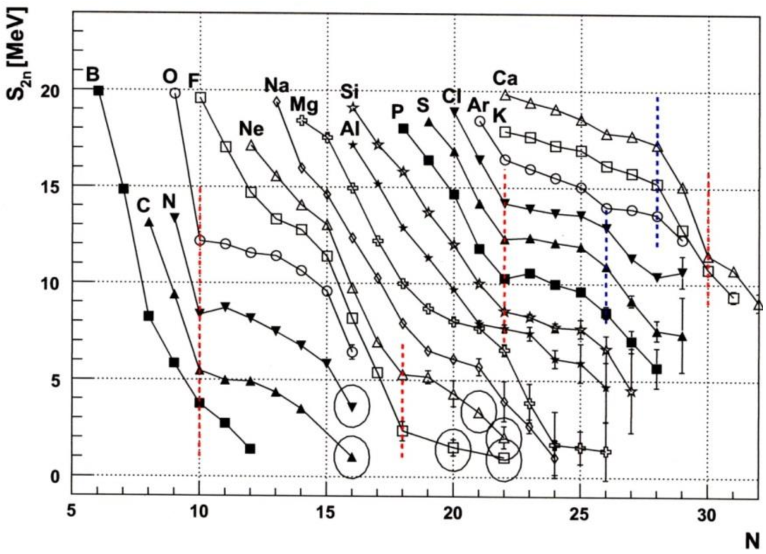


Fig. A5. Two-neuron separation energy S_{2n} vs. N – the drop points are visualized by vertical dotted red lines [Zdenek 2006, Fig. 8].

Figure A5 shows a strong effect of the magic number on S_{2n} and also reality of two-neutron transfer of exotic nuclei to outside and from surrounding neutron sea (cf-matter) if there it is. The nuclear transmutation induced by absorption of a nucleon cluster ${}^{A}_{Z}\Delta$ considered in the explanation of the CFP will be closely related to the two-neutron separation observed in nuclear physics.

A3. Diffusion coefficient of isotopes of hydrogen in Pd, Ni, and Cu

Diffusion constants may have close relation to the occurrence of the CFP.
In palladium (Pd), deuterium (D) has larger values of diffusion constant than protium (H) at a temperature region below 100°C as shown in Fig. A6, while a reversal occurs in higher temperature region than 500°C [Voelkl 1978 (Fig. 12.20), Fukai 1982, Fig. 4 and Table 2]. So, we can expect PdH_x is preferable than PdD_x for the CFP at the higher temperature region according to the mechanism based on the super-nuclear interaction proposed by us [Kozima 2006].

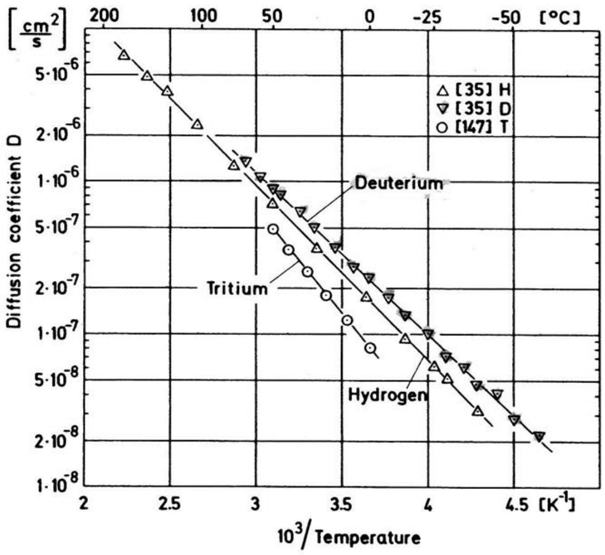


Fig. A6. Diffusion coefficient of isotopes of hydrogen in Pd (Numbers in brackets refer to References of original paper) [Voelkl 1978].

In Ni, the diffusion coefficients of H and D are normal, i.e. the light isotope diffuses faster than the heavy one as we see in Fig. A7. We observe the CFP in NiH_x easily than in NiD_x.

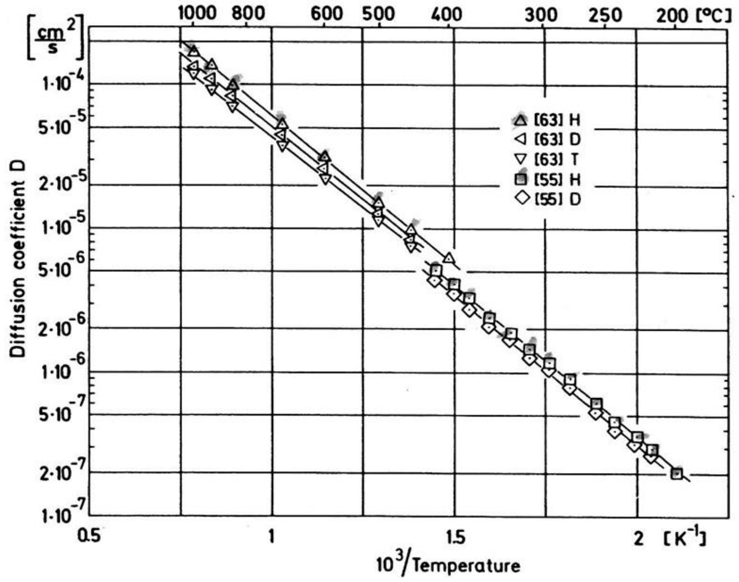


Fig. A7. Diffusion coefficient of isotopes of hydrogen in Ni (Numbers in brackets refer to References of original paper) [Voelkl 1978].

It is interesting to look into the diffusion data in Cu. As shown in Fig. A8, the diffusion coefficients of hydrogen isotopes in Cu is normal but measured only at a higher temperature region than 400 °C.

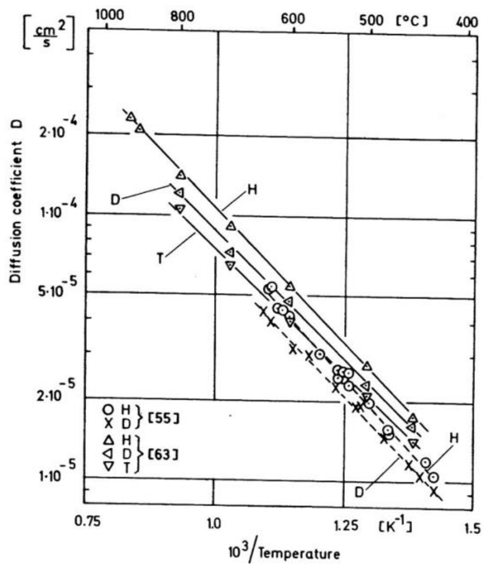
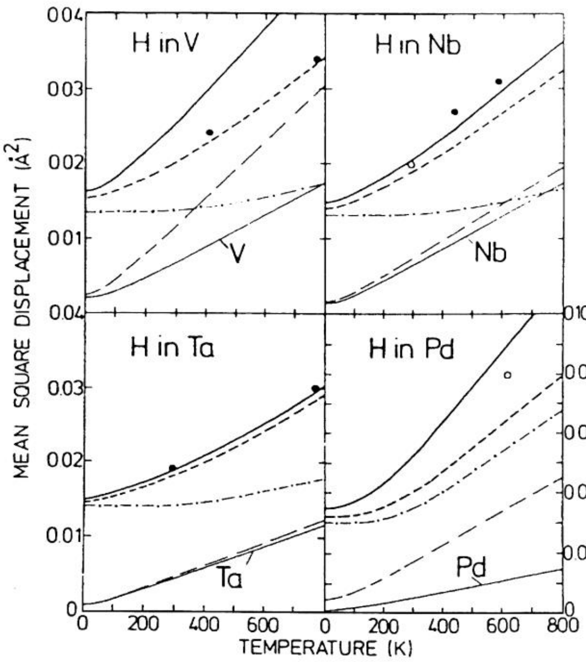


Fig. A8. Diffusion coefficient of isotopes of hydrogen in Cu (Numbers in brackets refer to References of original paper) [Voelkl 1978].

A4. Mean-square displacements of hydrogen atoms in V, Nb, Ta and Pd

The non-local characteristic of wavefunctions of hydrogen isotopes in cf-materials has been discussed in our papers and books and in Sec. A3 using the diffusion properties of D and H in them. The same tendency of hydrogen isotopes in cf-materials is also exhibited by using vibration amplitudes of D and H in them. The data sets shown in Fig. A9 are just only for protium H (not for deuterium D) in V, Nb, Ta and Pd but shows the non-localized characteristic of wavefunctions of H in Pd which is closely connected to the appearance of the CFP in Pd but not in other metals (V, Nb and Ta), from our point of view. The sharp increase of the vibration amplitude with temperature in Pd clearly shows the favor of higher temperatures for the CFP recognized and pointed out by many researchers hitherto.



Mean-square displacements. —: $\langle u^2\rangle^{\mathrm{H}}$ model I. --- :$\langle u^2\rangle^{\mathrm{H}}$ model II.--- :$\langle u^2\rangle^{\mathrm{H}}_{\mathrm{band}}$ model I. · — · — ·—:$\langle u^2\rangle^{\mathrm{H}}_{\mathrm{loc}}$ model I. —:$\langle u^2\rangle_{\mathrm{host}}$ [5.95]. Experimental values: • [5.96], Nb ○ [5.97], Pd ○ [5.98]

Fig. A9. The mean-square displacements for H in V, Nb, Ta, and Pd, consist of contributions from the localized and the band modes, $\langle u^2\rangle^{\mathrm{H}} = \langle u^2\rangle^{\mathrm{H}}_{\mathrm{loc}} + \langle u^2\rangle^{\mathrm{H}}_{\mathrm{band}}$, and each of these contributions can be calculated separately [Fukai 2005, Fig. 5.33]. The reference symbol as [5.95] etc. in the figure are those of original ones. Model I and II there are two models used to calculate the frequency spectrum of the hydrogen vibration from which $\langle u^2\rangle^{\mathrm{H}}$ was calculated.

Acknowledgement

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[DOE Report 2004] "*Report of the Review of Low Energy Nuclear Reactions.*"

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